Procedia Manufacturing
Volume 1, 2015, Pages 546–555
43rd Proceedings of the North American Manufacturing Research Institution of SME http://www.sme.org/namrc

Modulated Tool Path (MTP) Machining for Threading Applications

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Abstract
The modulated tool path (MTP) chip breaking process has been modified to improve chip management capabilities and to prevent large chip nest accumulations commonly encountered in threading operations. The use of MTP to create segmented chips requires a different approach for threading operations than for normal MTP turning operations, although the fundamental principal is the same. The primary difference between MTP for threading and for straight turning is that the part surface that the tool repeatedly engages and disengages, during the modulation process, is the thread root rather than the cut face. The threading MTP part program developed in this paper is capable of machining a thread with the desired lead, depth, undercut angle, and taper angle while also producing segmented chips.
Keywords: Modulated tool path (MTP), Lathe, Threading, Chip Management

1 Introduction

Chip management during CNC turning operations is a common issue in manufacturing environments. During conventional turning and threading operations, a single continuous chip is formed because the tool is continually engaged in the work-piece as the tool moves along the part. If the chip does not break and fall away from the machining area, it can collect to form a "chip nest". Interactions between the resulting chip nest and the rotating work-piece can be hazardous to the tool, work-piece and operator. Problems associated with chip nest buildup are especially prevalent in large scale internal threading operations. Here, the chips build up within the confined work-piece interior, often requiring the machine to be stopped for chip removal, threatening the quality of the final part outcome and the safety of the operator.

Several methods have been developed to reduce the effects of chip buildup by causing the chip to regularly break. Common chip breaking approaches include the use of, high pressure coolants, and

Peer-review under responsibility of the NAMRI Scientific Committee
doi:10.1016/j.promfg.2015.09.029

special chip breaking tool geometries (Graham, Smith 2008)0. However the effectiveness of these methods is dependent on the material being machined and the parameters of the cutting operation (Assaid 2010)0. In this paper, an alternative chip management technique is investigated for use in threading applications. During modulated tool path (MTP) threading, the tool repeatedly engages and disengages the work-piece under CNC program control and produces segmented chips which can be more easily removed from the machining environment.

2 MTP Machining

Modulated tool path (MTP) machining is a technique for controlling the length of chips being formed during turning operations (Tursky 2010). The general MTP process is illustrated in Figure 1. As the tool feeds along the part, tool point oscillations are programed which case the tool to oscillate tangent to the part surface. As the tool progresses, the oscillations cause interruptions in the chip formation process, and a single chip is formed with each oscillation. An advantage of MTP is that it produces segmented chips for all conditions without the need for additional hardware. The effectiveness of MTP machining as a chip management technique can be seen in Figure 2, which shows a significant reduction in chip buildup when MTP is used.

Thus far, MTP development has focused solely on turning applications (Adams 2008). In this work, MTP is adapted for chip-breaking during threading operations.

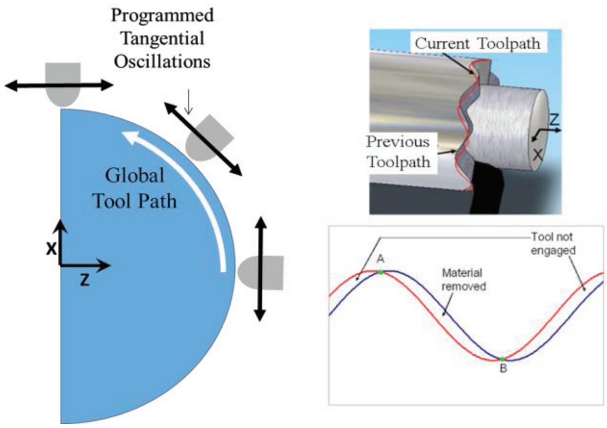

Figure 1. Tool-Surface interactions in MTP machining.

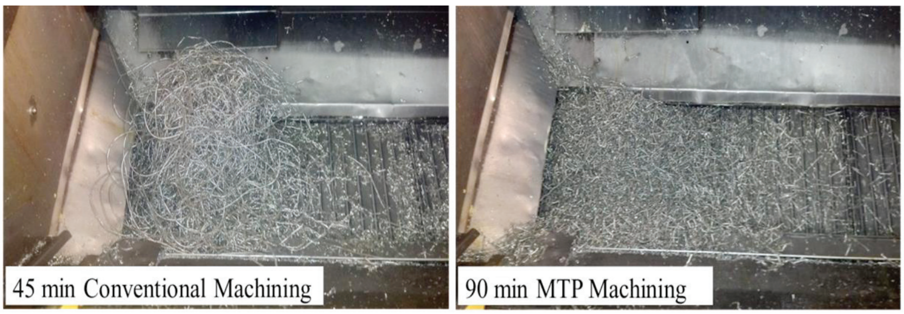

Figure 2. Chip buildup comparison between conventional (top) and MTP machining (bottom).

3 Adapting MTP for Threading

Adapting the MTP processes developed for profiling to multi-pass threading applications requires several significant changes, although the basic process of chip breaking is the same. The most significant conceptual change deals with the surface that the tool interacts with to break chips.

During profiling operations, the tool feeds continuously along the part profile, and the material surface that the tool interacts with is the surface that the tool left behind in the previous part rotation. As shown in Figure 1, oscillations in the tool feed direction tangent to the part surface cause the tool to engage and disengage the material along the feed direction. This concept is illustrated again in Figure 3 for profiling, where the tool interacts with the material surface in the global feed direction.

The primary difference for threading operations is that the tool does not encounter the same material surface from one rotation to the next. In order to create a threaded part, the feed per revolution is much larger than conventional turning and the tool machines away the "roots" of the thread while leaving the "peaks". During one full part revolution, the tool displaces along the global feed direction a distance equal to the thread lead, and the material that the tool encounters is separated from the surface left during the previous rotation by a thread peak. Assuming that the threading operation requires multiple passes to produce the final desired thread profile, the only material surface that the tool encounters during each pass is the thread root surface that was left behind during the previous pass. As such, the tool must oscillate in a direction normal to the root of the thread in order to generate the tool/surface interactions required to break chips. This process for threading operations is also illustrated in Figure 3.

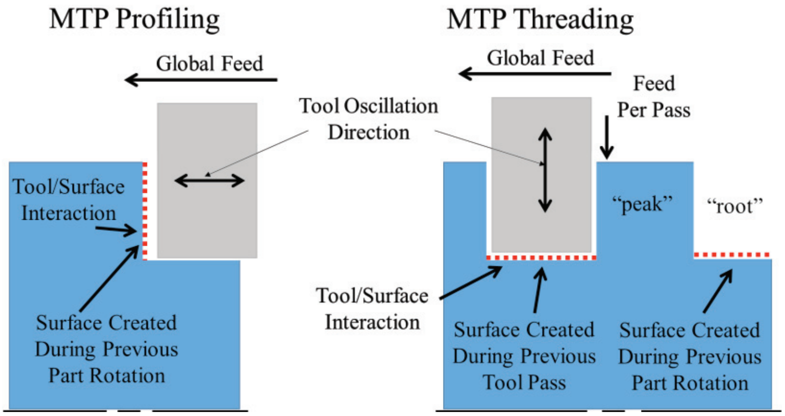

Figure 3: Illustration of the differing strategies for MTP profiling and threading, where tool oscillations interact with the surface left behind in the previous part revolution for profiling, and the surface left behind in the previous pass for threading.

4 MTP Threading

The basic process used to generate the tool/surface interactions required to break chips while threading is shown in Figure 4. Throughout the operation, tool point oscillations are superimposed onto the global threading feed, creating a wavy surface normal to the thread root. In Figure 4 the picture on the left shows a side view of the total motion of the tool as it feeds along the thread, and the other images show the tool/surface interactions which cause the chips to break. As the tool oscillates during one pass, it generates a wavy thread root surface which is represented by the blue shaded area. During the next tool pass, the tool is programmed to oscillate 180° out of phase from the tool motions in the previous pass, causing the tool to enter and exit the work-piece material once per tool oscillation. The number of chips which form is dependent on the number of tool oscillations which occur during one part rotation. Unlike MTP for profiling, whether or not chips break does not depend on the relationship between the spindle speed and the tool frequency (oscillations per revolution, or OPR), rather, it depends on the phasing of the tool motions between two subsequent passes.

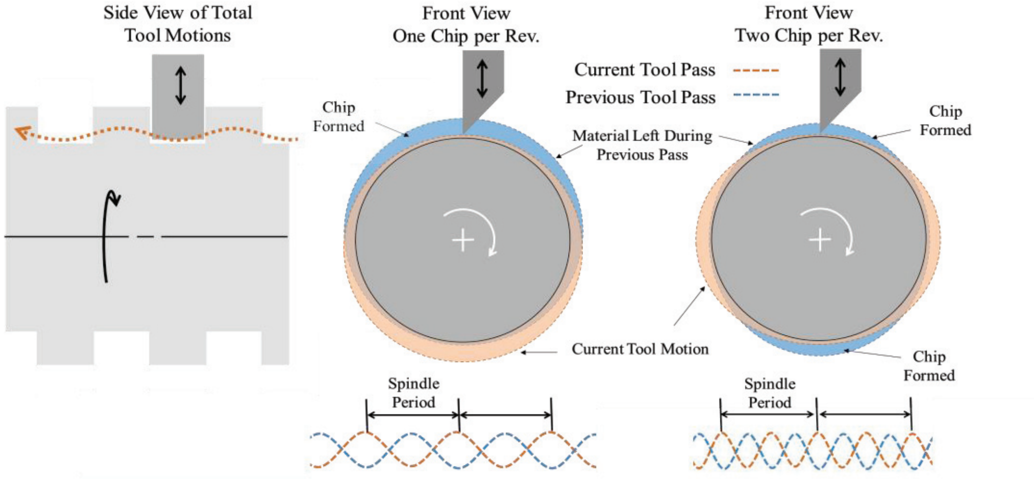

Figure 4: Illustration of MTP process for threading operations, where the tool repeatedly engages and disengages a wavy surface created during the previous tool pass.

The process for chip breaking shown in Figure 4 is applied to generate MTP threading part programs. The generation program is capable of accommodating straight and tapered threading operations at a desired infeed direction. The following parameters, labeled in Figure 5, are considered when generating an MTP threading part program:

- The thread lead, (L) (in the taper direction, θ_T),
- Spindle speed (RPM),
- Thread taper angle (θ_T),
- Tool infeed angle (θ_{in}) (to control chip formation or to account for thread geometry overhang),
- Thread depth (D) (in the infeed direction),
- Step increment per pass (f_p) (in the infeed direction),
- The number of tool oscillations per part rotation (OPR), and
- The oscillation amplitude relative to the feed per pass (Raf).

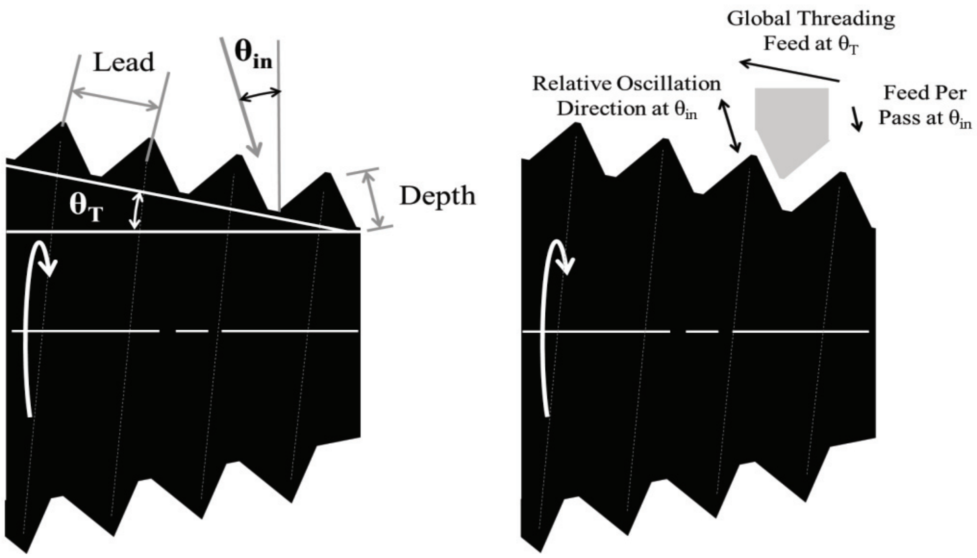

Figure 5: Thread parameters required to generate MTP threading part programs.

The threading part programs are created by commanding multiple linear motions which cause the tool to oscillate as it feeds along the thread. Figure 6 shows how the individual points are generated. The individual tool motions are determined by considering the total motion of the tool to be a combination of three separate motion components. The first motion component is the global threading feed which causes the tool to follow the path of the helical thread as the work-piece rotates. In the case of a tapered thread, the global threading feed must follow the helical thread along the path of the desired thread taper. The second motion component is the incremental feed per pass of the tool. The feed per pass acts in the infeed direction, $\theta_{in,}$ and determines the depth of cut and the amount of material which is removed along the thread during a single pass.

The first two motion components are common to both MTP and standard threading. To break chips using MTP, a third motion component is required which causes the tool to oscillate. The oscillations are commanded to be in the direction of the infeed angle, θ_{in}, to prevent the tool point oscillations from interfering with the final thread geometry. In order to reduce the total number of individual linear moves required to generate the tool point oscillations, a simple 2-point oscillation, or "zig-zag", approach is used, which produces oscillatory motions with only two motion commands per cycle.

5 MTP Move Calculation

The total resulting motion of the tool throughout the operation can be seen in Figure 6. During each pass the tool follows the global threading path at the taper angle, θ_T, with a superimposed oscillation along the infeed angle. The tool oscillations are commanded such that the tool moves back and forth along the infeed angle relative to the thread geometry (see Figure 6 top), resulting in a global "zig-zag" motion relative to the machine axes (see Figure 6 bottom). At the start of each new pass, the tool is shifted by the incremental feed per pass in the infeed direction. As the tool starts each new pass, the oscillations are 180 degrees out of phase with the oscillations of the previous pass so that the tool repeatedly engages and disengages the thread root and creates segmented chips.

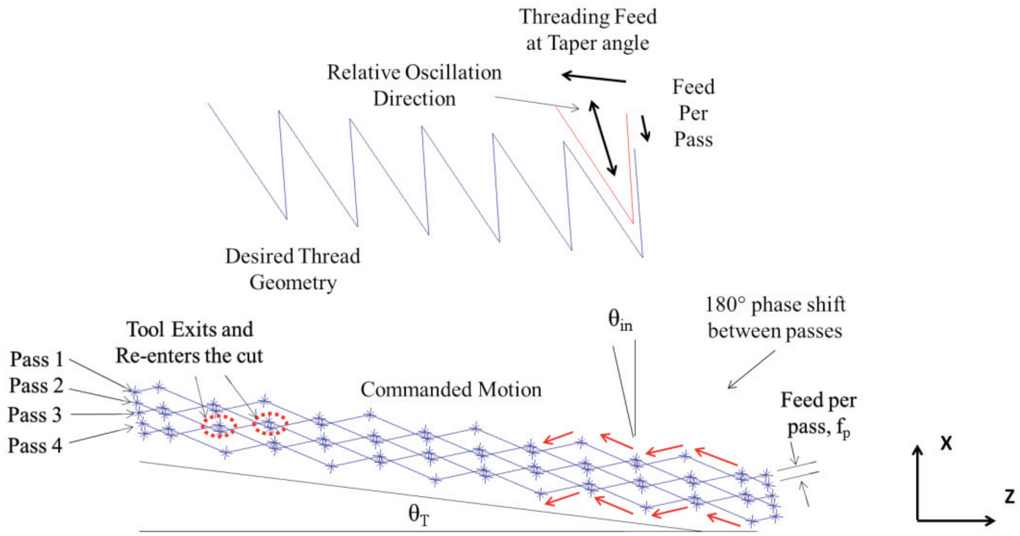

Figure 6: Depiction showing the process of creating the MTP motions based on three individual motion components (threading feed, feed per pass, and tool oscillations).

Each individual move segment is calculated by summing together each motion component. The use of a 2-point wave requires two linear moves for each oscillation of the tool so that the total number of linear moves per pass is dependent on the number of total oscillations. A detailed view of the motion component vectors and the commanded oscillation motions is shown in Figure 7, where the global lead vector components, V_L, and the oscillation vector components, V_O, combine to locate the x and z coordinates, at P, for each move. The wavelength and the amplitude of the oscillations are determined based on the input parameters of the operation. The amplitude is designated relative to the feed per pass, f_p, through the parameter Raf, where amplitude $A = f_p Raf$. Note that Raf values should be greater than 0.5 in order to create segmented chips. The oscillation wavelength is dependent on the lead and the number of oscillations per part revolution, OPR, where the wavelength is equal to L/OPR.

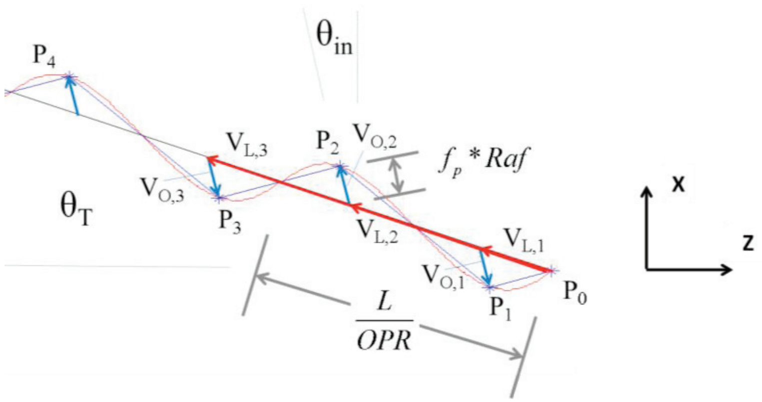

Figure 7: Motion components used to program MTP moves, where the wavy red line represents a superimposed sine wave oscillation, and the blue line is a commanded two point sine wave approximation.

The x and z coordinates for the moves in a single pass are calculated based on the input parameters, using Equation (1.1) and (1.2). In subsequent passes, the x and z coordinates of the lead vectors, V_L, are shifted in the infeed direction, and the oscillation vectors, V_O, are reversed so that each pass is 180° out of phase with the previous pass. When plotted together, the oscillation motion of each pass should cross over the tool path in the previous pass, as shown in Figure 6.

$$P_{x,N} = \begin{cases} \dfrac{L\sin(\theta_T)}{OPR}\left(\dfrac{N-1}{2}+\dfrac{1}{4}\right) - f_p Raf\cos(\theta_{in}),\ N\ is\ odd \\ \dfrac{L\sin(\theta_T)}{OPR}\left(\dfrac{N}{2}+\dfrac{3}{4}\right) + f_p Raf\cos(\theta_{in}),\ N\ is\ even \end{cases} \tag{1.1}$$

$$P_{z,N} = \begin{cases} -\dfrac{L\cos(\theta_T)}{OPR}\left(\dfrac{N-1}{2}+\dfrac{1}{4}\right) + f_p Raf\sin(\theta_{in}),\ N\ is\ odd \\ -\dfrac{L\cos(\theta_T)}{OPR}\left(\dfrac{N}{2}+\dfrac{3}{4}\right) - f_p Raf\sin(\theta_{in}),\ N\ is\ even \end{cases} \tag{1.2}$$

The final step is to determine the velocities required for each motion to correctly synchronize the motions of the tool with the motions of the spindle. The velocities are found by determining the total distance traveled during each move, d_{move}, and the total time the move should take. The time for each move is based on the frequency of the tool which is dependent on the spindle speed and the OPR. The time per move is calculated as $t_{move} = 1/(2\omega_{tool})$ for a 2-point sine wave, where $\omega_{tool} = 60 * OPR/RPM$, and the resulting velocity for each move is $V_{move} = d_{move}/t_{move}$.

Note that the final pass is created without oscillations to prevent a wavy surface on the final thread root.

6 Parameter Selection Considerations

MTP operations are defined by two parameters which define the tool oscillation frequency relative to the spindle speed (OPR), and the tool amplitude relative to the feed per revolution (Raf). For turning applications, these parameters have been investigated to determine their effects on surface finish and chip length (McFarland 2010; Tursky 2010; Berglind and Ziegert 2013). For threading applications the effects of MTP on surface finish are less of a concern because it is assumed that at least the final pass is a standard threading pass with a profiled tool (so the final thread root surface is not created while the tool is oscillating). The focus of this discussion is on how the MTP parameters used for threading effect the chip length and the cutting forces.

The resulting chip length is determined by finding the ratio of time that the tool is in the cut during one tool oscillation assuming a 180° oscillation offset between passes and a two point sine approximation. A schematic of this process is shown in Figure 8, where the tool enters and exits the cut during one oscillation. The chip length is found as the circumferential distance that the material flows past the tool while the tool is engaged in the cut. The chip length is calculated using Equation (1.3), where $\pi D/OPR$ is the circumferential length of material flowing past the tool during one oscillation period, and $(2Raf+1)/4Raf$ represents the ratio of time that the tool is engaged during one oscillation. Note that if the tool engagement ratio is greater than one, then the tool amplitude is not large enough to break chips, so the minimum value of Raf is 0.5 for segmented chips to form.

Also note that the chip length calculation in Equation (1.3) does not account for chip compression or chip curling during the cutting process.

$$Length = \frac{\pi D}{OPR}\left(\frac{2Raf+1}{4Raf}\right) \tag{1.3}$$

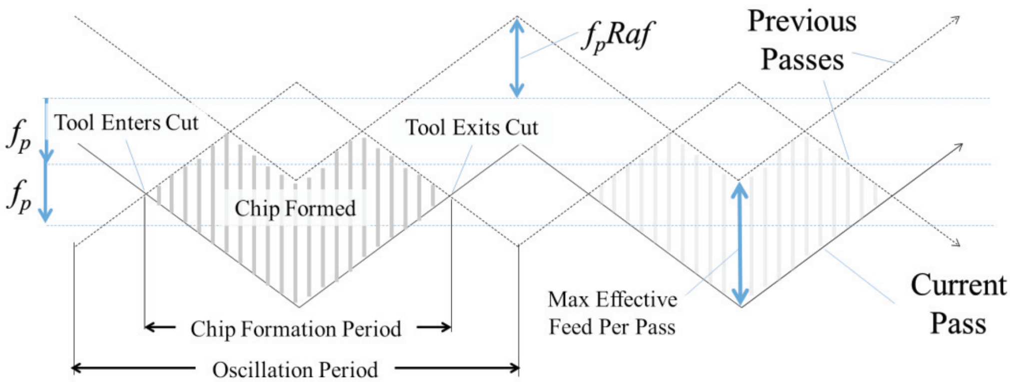

Figure 8: Schematic showing one tool pass relative to the previous two tool passes, where new chips are formed whenever the tool passes beyond the previous tool locations.

As the actual cutting forces during threading are highly dependent on the specific operation (thread profile, approach angle, material, etc.), the discussion of cutting forces here will focus on how the MTP parameters effect the maximum effective feed per pass relative to the commanded global feed per pass. One drawback of MTP machining is that in order to generate segmented chips the tool must disengage from the work piece for some period of time. As a result, there are some periods when there is no material removal, and some periods when the tool is not engaged at full capability. To maintain global material removal rates there must be some periods when more material is being removed to compensate for the periods when less, or no material is removed. This can be seen in Figure 8, where the maximum effective feed per pass, when the chip thickness is greatest, is greater than the global feed per pass, f_p, by a factor of two. As such, the cutting forces during MTP threading vary between zero and some maximum value during each oscillation, where the maximum value is equal to the cutting forces during standard threading when the feed per pass is doubled.

7 Preliminary MTP Threading Tests

A preliminary MTP threading test was conducted on an Okuma LC-30 Lathe with a retrofitted GBI controller. Two threaded parts were created, one using the standard threading approach, and the other using the MTP Threading Program. During these tests the parameters listed in

Table 1 were used to generate the part programs. In Figure 9 the two resulting parts are shown along with the chips that were formed during the operations. For each part, five passes were made to form an effective thread root depth of 0.025 inches. It can be seen from the two resulting parts that MTP program was able to successfully generate the same thread as the non-MTP threading program. Furthermore, the ability to generate segmented chips using the methods discussed in this paper is demonstrated in this test, where the chips formed using MTP are significantly shorter than the single continuous chips formed without MTP.

Table 1: Parameters used for preliminary MTP threading tests

Variable	Value
Lead	0.5 inch
Spindle Speed	50 RPM
Thread taper angle, θ_T	0 degrees
Tool approach angle, θ_A	0 degrees
Step increment per pass	0.005 inch
OPR	2
Raf	1
Material	Aluminum
Diameter	6 inch

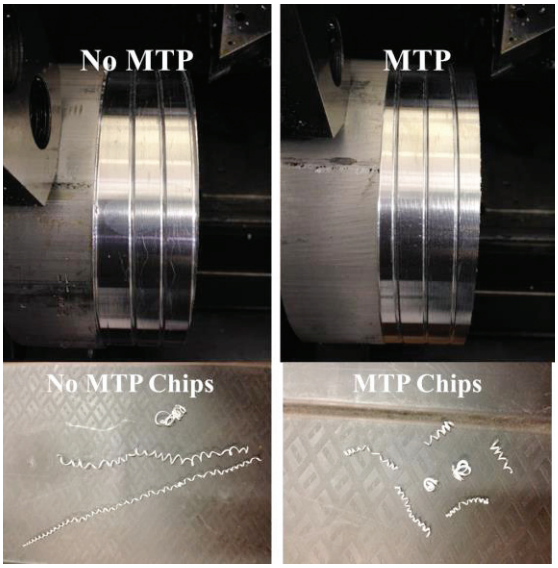

Figure 9: Resulting parts generated using MTP and non-MTP threading programs and the chips formed during each operations.

8 Conclusion

Chip management is a common issue in turning and threading applications and MTP machining has been shown to be an effective means of avoiding chip nest buildup without the need for external hardware or specialized tooling in both application. The threading tests showed that the MTP program successfully generated regular segmented chips which reliably fell away from the cutting tool. Although tested here for the simplest case, the process for generating MTP threading programs is able to accommodate tapered threads and variable infeed approach angles to produce undercut threads.

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